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A Preliminary Study on Steam Condensation with Air-Helium Mixture on a Vertical Tube for Low Subcooling Condition

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1. Introduction

The Passive Containment Cooling System (PCCS) is introduced for nuclear power plants to maintain the integrity of containment in accident conditions. The PCCS removes decay heat by condensing steam inside the containment. Therefore, it is essential to evaluate the condensation heat transfer in various conditions to precisely predict the performance of the PCCS.

Numerous researches have conducted to investigate the thermal-hydraulic effects on the condensation heat transfer. Especially, many researches focused on how the presence of noncondensable gases affect the condensation. For instance, researchers such as Uchida [1], Tagami [2], Su [3, 4], Dehbi [5] and Lee [6] have experimentally studied condensation heat transfer in steam-air mixture. They reported that the presence of air dramatically decreases the condensation heat transfer.

Meanwhile, when severe accident occurs in nuclear power plant, hydrogen is produced by the cladding oxidation and molten corium concrete interaction. The existence of hydrogen may affects the condensation heat transfer, as it have high diffusivity and low density when compared with the air. Liu [7] reported that the condensation heat transfer decreased by 20% until the mole fraction of helium in total noncondensable gases reaches 30%. Dehbi [5] and Su [3, 4] reported that the condensation heat transfer can be changed according to helium mass fraction. Note that, due to hydrogen explosion risk, helium is used instead of hydrogen in all experiments.

In this paper, we experimentally analyzed how presence of helium affects the condensation heat transfer. The experiment results were compared with the other open experiment datasets for validation purpose. The experiment result show that the existence of helium gas can decrease the condensation heat transfer.

2. Experiment Method

2.1 Experiment apparatus

The schematic diagram of the condensation experiment apparatus used in this study is shown in Fig. 1. The steam-side of the experiment facility consists of pressure vessel, condensing tube and a boiler which supplies steam to the pressure vessel. The dimension of the pressure vessel is 2500 mm in axial direction, and 447.2 mm in radial direction. A vertically oriented stainless-steel tube with an outer diameter of 38.1 mm and a length of 1100 mm was used as condensing tube. The coolant side of the experiment facility includes a heat exchanger and a chiller, which can maintain the coolant temperature during the experiments. The chiller has 6.5 kW cooling capacity, which is enough to maintain the coolant temperature in the conditions we considered.

The temperature of the gas mixture, the condensing tube wall and the coolant were measured with K-type thermocouples. 14 thermocouples were used for measuring bulk temperature, 21 thermocouples were used for wall temperature, and 7 thermocouples were used for obtaining the coolant temperature. The wall temperature of an axial position is obtained by averaging the temperature measured by 3 thermocouples which located to have 120° degree with each other. The condensing tube was divided by 4 groups, and the location of the thermocouples were determined so that the heat transfer coefficient of each group could be evaluated. The location of installed thermocouples is shown in Fig. 2.

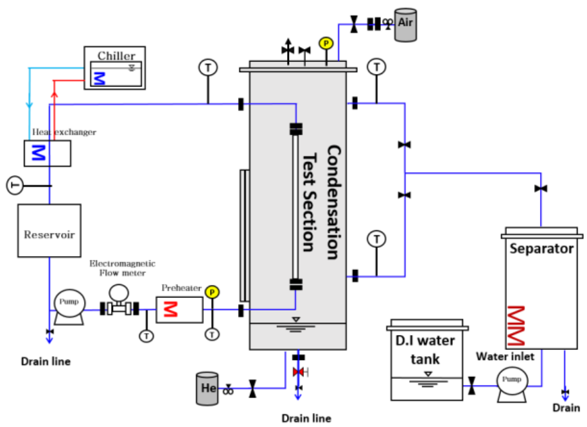

Fig. 1. Schematic diagram of the experimental apparatus.

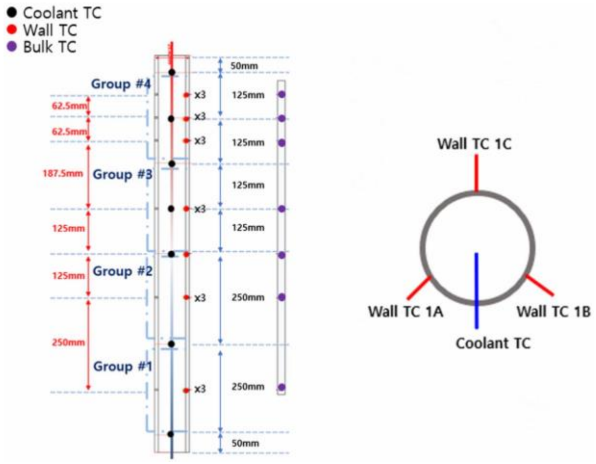

Fig. 2. Location of the installed thermocouples.

2.2 Experiment procedure and data reduction

Table I: Experiment Conditions

	Pressure (bar)	Subcooling (K)	NC mass fraction	X_{he}/X_{air}
Range	2, 3	13-29	0.3-0.5	0.08-0.39

The experiment conditions are presented in Table 1. 'X' and 'NC' represents for mole fraction and noncondensable gas. To evaluate the fraction of noncondensable gases, we first vacant the pressure vessel, and then injected helium and air, respectively. The mass fraction of noncondensable gases are calculated using the ideal gas law. Thereafter, the steam is supplied to reach the steady-state of desired condition. As it takes more than 3-4 hours to reach the steady-state, the gas mixture inside pressure vessel was thought to be fully mixed. After reaching steady-state, we measured the data required to calculate heat transfer coefficient for 100 minutes, and then end the experiment procedure.

The local heat transfer coefficient can be obtained from the following equation:

$$h = \frac{\dot{m}c_p\left(T_{c,o}-T_{c,i}\right)}{2\pi rL\left(T_\infty - T_w\right)} \tag{1}$$

where $\dot{m}, T_{c,o}, T_{c,i}, T_\infty$ and T_w represent for coolant mass flow rate, coolant outlet temperature for each group, coolant inlet temperature for each group, bulk temperature and wall temperature, respectively. The average heat transfer coefficient was obtained by arithmetically averaging local heat transfer coefficient of 4 groups.

The uncertainty of each experiment data was conducted. The uncertainties of the average heat transfer coefficients were about 13.1 %.

3. Results and discussions

In Fig. 3, the experiment results are shown. Two types of noncondensable gases, one with only air, and the other with air-helium mixture were tested. Although the total noncondensable gas mass fraction is same, the steam condensation heat transfer was decreased by about 20% when helium present. Such result is consistent with the conclusion of Liu [7], which reported that the heat transfer coefficient was decreased by 20% when the content of helium in noncondensable gas mixture is less than 30 %.

Also, it may be noticed that the difference of two cases getting bigger when total noncondensable gas mass fraction is small. This is attributed to the ratio of helium over total noncondensable gases is getting larger. Therefore, we tested various X_{he}/X_{NC} and its results were shown in Fig. 4. Note that, the air mass fraction kept constant for all cases. We compared the experiment data with the correlation proposed by Dehbi [5]. Dehbi's correlation for condensation in presence of air-helium mixture is as follows:

$$\bar{h}_L = \frac{L^{0.05}\left\{(3.7+28.7P)-(2438+458.3P)\log\left(\frac{29(X_{He}+X_A)}{29(X_{He}+X_A)+18X_s}\right)\right\}}{\left(\bar{T}_\infty-\bar{T}_w\right)^{0.25}} * \left\{1.051-1.149X_{He}-0.0553X_A+1.371\left[(X_{He})^2+X_{He}X_A\right]\right\} \tag{2}$$

where Dehbi's correlation for steam-air mixture is:

$$\bar{h}_L = \frac{L^{0.05}\left\{(3.7+28.7P)-(2438+458.3P)\log(W_a)\right\}}{\left(\bar{T}_\infty-\bar{T}_w\right)^{0.25}} \tag{3}$$

Note that, the heat transfer coefficient of the 38 mm outer diameter case can be achieved by multiplying 1.25 to the Eqs. (2) and (3) [5].

The comparison result shows that the experiment result fitted with the correlation of Dehbi. We used Dehbi's correlation for steam-air mixture as a reference of comparison. By comparing the correlations and experiment result, we found out that the as the helium mass fraction increases, the degree of heat transfer coefficient degradation increases.

Fig. 5 shows the heat transfer coefficient for various subcooling. In both conditions, one with only air and one with air and helium, heat transfer decreases as the subcooling increases. However, the sensitivities to the degree of subcooling of two conditions are different. In the steam-air-helium case, the subcooling effect is less than the steam-air case. This can be explained with the local concentration of the noncondensable gases. As the wall subcooling increases, more noncondensable gases accumulate in vicinity of the tube, due to the vigorous condensation. However, as the helium is a high diffusivity gas, accumulated helium near the tube diffuses to the bulk gas. This reduces the total noncondensable content near the tube wall, decreasing the subcooling effect on condensation.

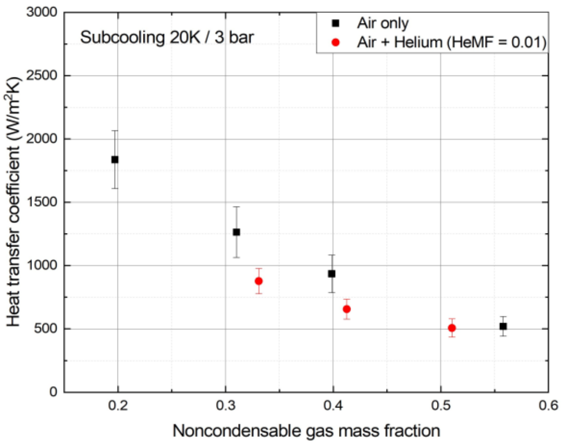

Fig. 3. Comparison of condensation in steam-air mixture and steam-air-helium mixture conditions.

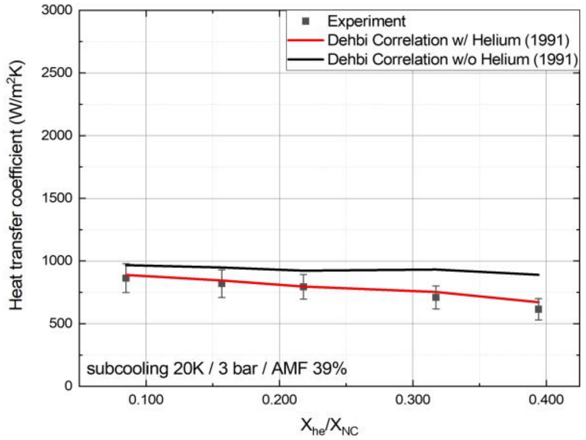

Fig. 4. Heat transfer coefficient for various helium mass fraction.

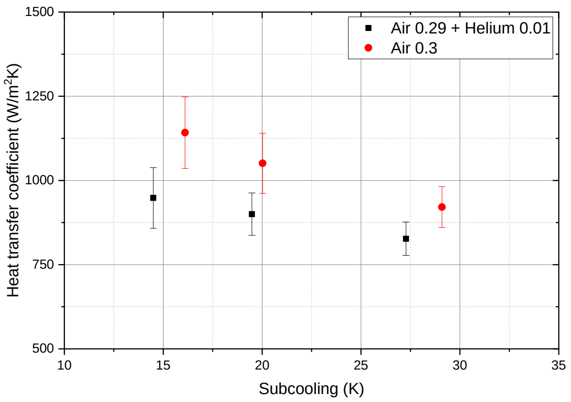

Fig. 5. Heat transfer coefficient changes along various subcooling degree.

4. Conclusions

In this paper, we experimentally investigated the effect of hydrogen concentration on the steam condensation. With a tube of 38.1 mm outer diameter and 1100 mm length, we tested noncondensable gas mass fraction from 0.3 to 0.5. The range of the helium fraction in noncondensable gas mixture we tested was 0.08 to 0.39. According to the experiment results, only small amount of helium in gas mixture degraded condensation heat transfer coefficient by about 20%. The experiment result was well fitted with the correlation proposed by Dehbi, which showed the validity of the experiment results. The comparison of experimental data with the correlation which does not consider helium presence, showed that the degree of heat transfer degradation is proportional to the helium content.

Finally, we analyzed the effect of subcooling on condensation heat transfer when helium presents. The experiment results showed that, when helium exists, the subcooling effect on condensation decreases, which can be explained with the local fraction of the noncondensable gas in vicinity of condensing tube wall and diffusion mass transfer.

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REFERENCES

[1] H. Uchida, A. Oyama, Y. Togo, Evaluation of post-incident cooling systems of light water power reactors, Tokyo Univ., 1964.

[2] T. Tagami, Interim report on safety assessments and facilities establishment project for June 1965, No. 1, Japanese Atomic Energy Research Agency, (1965).

[3] J. Su, Z. Sun, M. Ding, G. Fan, Analysis of experiments for the effect of noncondensable gases on steam condensation over a vertical tube external surface under low wall subcooling, Nuclear Engineering and Design, 278 (2014) 644-650.

[4] J. Su, Z. Sun, G. Fan, M. Ding, Experimental study of the effect of non-condensable gases on steam condensation over a vertical tube external surface, Nuclear Engineering and Design, 262 (2013) 201-208.

[5] A.A. Dehbi, The effects of noncondensable gases on steam condensation under turbulent natural convection conditions, Massachusetts Institute of Technology, 1991.

[6] Y.-G. Lee, Y.-J. Jang, D.-J. Choi, An experimental study of air–steam condensation on the exterior surface of a vertical tube under natural convection conditions, International Journal of Heat and Mass Transfer, 104 (2017) 1034-1047.

[7] H. Liu, N. Todreas, M. Driscoll, An experimental investigation of a passive cooling unit for nuclear plant containment, Nuclear Engineering and Design, 199(3) (2000) 243-255.